Method of generating spin-polarized conduction electron and semiconductor device

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Abstract

A semiconductor device for generating spin-polarized conduction electrons including a ferromagnetic semiconductor layer and a non-magnetic semiconductor layer having a band alignment of Type II with respect to the ferromagnetic semiconductor, said ferromagnetic semiconductor layer and non-magnetic semiconductor layer being connected together directly or with interposing therebetween another non-magnetic semiconductor layer or energy barrier layer such that a spin splitting of a conduction band of the non-magnetic semiconductor layer is induced by a spontaneous spin splitting of a valence band of the ferromagnetic semiconductor layer, and spin-polarized conduction electrons are generated in the non-magnetic semiconductor layer by the spin splitting of the conduction band of the non-magnetic semiconductor layer.

Description

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to a method of generating spin-polarized conduction electrons in a semiconductor device. The present invention also relates to a semiconductor device in which spin-polarized conduction electrons are generated.

[0003] 2. Related Art Statement

[0004] Generation of spin-polarized conduction electrons in a semiconductor material newly applies spin degree of freedom to semiconductor electronic materials, and has been studied towards a future device application. Semiconductor devices generating such spin-polarized conduction electrons are expected to realize a novel application to a spin field effect transistor, a spin-polarized scanning tunneling microscopy, a spin memory device, a circularly polarized light emitting device, etc.

[0005] In a conventional technology of generating spin-polarized electrons, spin-polarized electrons are injected into a semiconductor body by using metallic magnetic electrodes. However, in this known method, the spin-polarization generated within the semiconductor body is changed only slightly owing to the Schottky barrier produced at a metal/semiconductor interface.

[0006] It is possible to generate spin-polarized electrons by replacing a part of atoms constituting a semiconductor material with magnetic atoms to convert the non-magnetic semiconductor material into a magnetic semiconductor material. However, since the interaction between magnetic spins and electrons is small, the spin polarization is produced only slightly. On the other hand, the interaction between holes in such a magnetic semiconductor and magnetic spins is relatively large and it is possible to give big spin polarization to holes. But a spin relaxation time is very short because of the spin-orbit interaction, and thus the application to the field of electronics is difficult.

SUMMARY OF THE INVENTION

[0007] Therefore, the purpose of this invention is to provide a method of generating effectively spin-polarized electrons (carriers in the conduction band) within a semiconductor.

[0008] It is another object of this invention to provide a semiconductor device, in which spin-polarized conduction electrons can be effectively generated.

[0009] According to the invention, a method of generating spin-polarized conduction electrons, characterized in that the method comprises a step for providing a ferromagnetic/non-magnetic heterojunction between a ferromagnetic semiconductor layer and a non-magnetic semiconductor layer having an energy band alignment of Type II with respect to the ferromagnetic semiconductor layer such that a spin splitting of a conduction band of the non-magnetic semiconductor layer is induced by a spontaneous spin splitting of a valence band of the ferromagnetic semiconductor layer to generate spin-polarized conduction electrons in the non-magnetic semiconductor layer.
[0010] In the Type II energy band alignment of semiconductor layers, a top of the valence band of one semiconductor layer is located above a bottom of the conduction band of the other semiconductor layer in the energy band diagram. If the ferromagnetic semiconductor layer is connected to the non-magnetic semiconductor layer having the energy band alignment of Type II with respect to the ferromagnetic semiconductor layer, the spontaneous spin splitting of the valence band of the ferromagnetic semiconductor layer induces the spin splitting of the conduction band of the adjacent non-magnetic semiconductor layer and spin-polarized electrons are generated in the non-magnetic semiconductor layer.
[0011] According to the invention, a semiconductor device, characterized in that the device comprises a ferromagnetic semiconductor layer, and a non-magnetic semiconductor layer having an energy band alignment of Type II with respect to the ferromagnetic semiconductor, said ferromagnetic semiconductor layer and non-magnetic semiconductor layer being connected to form a ferromagnetic/non-magnetic heterojunction such that a spin splitting of the conduction band of the non-magnetic semiconductor layer is induced by a spontaneous spin splitting of the valence band of the ferromagnetic semiconductor layer to generate spin-polarized conduction electrons in the non-magnetic semiconductor layer.
[0012] The method for generating the spin-polarized conduction electrons according to the invention utilizes the fact that the spontaneous spin splitting of the valence band is induced in the magnetic semiconductor, and when the magnetic semiconductor is adjoined to the non-magnetic semiconductor having the energy band alignment of Type II with respect to the magnetic semiconductor layer, the spin splitting of the conduction band of the non-magnetic semiconductor is induced by said spontaneous spin splitting of the valence band of the magnetic semiconductor to generate spin-polarized electrons in the non-magnetic semiconductor.

BRIEF DESCRIPTION OF THE DRAWINGS
[0013] FIG. 1 is a schematic diagram showing the conventional junction of non-magnetic semiconductors;
[0014] FIG. 2 is a schematic diagram illustrating the ferromagnetic/non-magnetic heterojunction according to the invention;
[0015] FIG. 3 is a schematic view depicting an embodiment of the semiconductor device according to the invention;
[0016] FIG. 4 is a perspective view showing a circularly polarized light emitting device according to the invention;
[0017] FIG. 5 is a schematic view illustrating a spin-polarized field effect transistor according to the present invention;
[0018] FIG. 6 is a schematic diagram representing another embodiment of the ferromagnetic/non-magnetic heterojunction for realizing the method according to the invention; and
[0019] FIG. 7 is a schematic diagram showing still another embodiment of the ferromagnetic/non-magnetic heterojunction according to the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS
[0020] As explained above, the junction of semiconductors in which the conduction band of one semiconductor and the valence band of the other semiconductor are partially overlapped with each other is called the Type II junction. Now the Type II junction between a non-magnetic semiconductor and a ferromagnetic semiconductor used in the method according to the invention will be explained in comparison with the conventional Type II junction between non-magnetic semiconductors.
[0021] FIG. 1 is a schematic diagram showing the conventional Type II junction of semiconductors. In this junction, a material 11 is a non-magnetic semiconductor such as GaSb, and a material 12 is a non-magnetic semiconductor such as InAs. These semiconductor materials reveal the Type II band alignment upon being connected each other. A graph shown in a lower left of the drawing of FIG. 1 expresses the density of states of the valence band of the material 11, and a graph shown in an upper right represents the density of states of the conduction band of the material 12. In these graphs, a vertical coordinate y denotes energy E (eV) and a horizontal coordinate x represents wave number k (m). At a middle area of the diagram, there is shown the energy band in this junction, wherein a vertical coordinate y denotes energy E (eV) and a horizontal coordinate x represents a position x(m). In the conventional junction, the spin splitting of the density of states of the valence band of the material 11 is

not occurred, and therefore the spin polarization is not induced on the conduction band of the material 12.

[0022] FIG. 2 shows the ferromagnetic/non-magnetic semiconductor heterojunction of Type II used in the method of generating the spin-polarized conduction electrons according to the invention. In this ferromagnetic/non-magnetic semiconductor heterojunction, a material 21 is the ferromagnetic semiconductor such as (Ga,Mn)Sb, and a material 22 is the non-magnetic semiconductor such as InAs. When these semiconductor materials are connected to each other, the Type II band alignment is obtained. Similar to FIG. 1, a lower left graph of FIG. 2 expresses the density of states of the valence band of the material 21 and an upper right graph denotes the density of states of the conduction band of the material 22, wherein a vertical coordinate y denotes the energy E (eV) and a horizontal coordinate x represents the wave number k (m). Furthermore, a middle graph of FIG. 2 shows the energy band in this junction, wherein a vertical coordinate y shows the energy E (eV) and a horizontal coordinate x denotes the position x(m). In such a ferromagnetic/non-magnetic semiconductor heterojunction, the spin splitting of the valence band of the ferromagnetic semiconductor material 21 occurs spontaneously due to the exchange interaction between magnetic spins and holes. Then, the density of states of the conduction band of the non-magnetic semiconductor material 22 connected to the ferromagnetic semiconductor material 21 resonates in energy with the valence band of the ferromagnetic semiconductor material 21, the spin splitting is induced in the conduction band of the non-magnetic semiconductor material 22 by the proximity effect and the spin injection effect, and the spin-polarized electrons are generated in the non-magnetic semiconductor material 22.

[0023] FIG. 3 is a schematic view showing the structure of an embodiment of the semiconductor device 30 having the ferromagnetic/non-magnetic semiconductor heterojunction according to the invention. On a semiconductor substrate 32, an electronic and/or optical device structure 34 is formed by any one of the well developed thin film manufacturing processes. Then, a non-magnetic semiconductor layer 36 and a ferromagnetic semiconductor layer 38 are grown on the electronic and/or optical device structure 34 by the molecular-beam-epitaxy method. In the present embodiment, the non-magnetic semiconductor layer 36 is made of InAs and the ferromagnetic semiconductor layer 38 is made of (Ga,Mn)Sb.

[0024] It should be noted that according to the invention, the magnetic semiconductor layer 38 may be made of other transition metal elements or other rare earth elements. These semiconductor material crystals can be created by the thin film crystal creating methods such as the molecular-beam-epitaxy method. Although the (Ga,Mn)Sb layer 38 may be grown at a high temperature near 550 degrees centigrade, the (Ga,Mn)Sb layer is preferably grown at a non-equilibrium extremely lower temperature (for example, about 250 degrees centigrade), because the solid solubility of magnetic element (Mn) in the III-V family semiconductor is very low.

[0025] In the semiconductor device 30, the spin-polarized electrons are generated in the non-magnetic semiconductor layer 36 as explained above with reference to FIG. 2, a new degree of freedom, i.e. the electron spin is introduced in the electronic and/or optical device structure 34. In the embodiment shown in FIG. 3, the electronic and/or optical device structure 34 and non-magnetic semiconductor layer 36 are formed by the separate semiconductor layers. However, when the semiconductor device 30 is constructed as another semiconductor device such as a spin-polarized field effect transistor in which the non-magnetic semiconductor layer 36 itself can serve as the electronic and/or optical device structure, the electronic and/or optical device structure 34 may be dispensed with.

[0026] FIG. 4 is a perspective view showing another embodiment of the semiconductor device according to the invention. In the present embodiment, the semiconductor device is constructed as a circularly polarized light emitting device 40. The circularly polarized light emitting device 40 comprises a semiconductor substrate 42, a light emitting device structure 44 formed on the semiconductor substrate 42, a non-magnetic semiconductor layer 46 grown on the light emitting device structure 44, and a ferromagnetic semiconductor layer 48 formed on the non-magnetic semiconductor layer 46. This structure is similar to that of the semiconductor spin device 30 shown in FIG. 3. In this circularly polarized light emitting device 50, a deflection of the circularly polarized light can be controlled by the interaction between the light and the spin-polarized electrons induced in the non-magnetic semiconductor layer 46.

[0027] FIG. 5 is a schematic sectional view illustrating the structure of another embodiment of the semiconductor device according to the invention. In the present embodiment, the ferromagnetic/non-magnetic semiconductor heterostructure according to the invention is applied to a spin-polarized electronic injecting electrode. The semiconductor device is constructed as a spin-polarized field effect transistor 50. The spin polarized field effect transistor 50 comprises a general lateral type field effect transistor structure 51 including a semiconductor substrate 52, source and drain regions 53 and 54 and a gate insulating layer 54. On the source and drain regions 53 and 54, non-magnetic semiconductor layers 56 and ferromagnetic semiconductor layers 57 are successively grown to form the spin-polarized electronic injecting source and drain electrodes, and a DC voltage source 58 is connected across these electrodes. The spin-polarized field effect transistor has been discussed in S.Datta and B.Das, App. Phys. Lett. 56,665 (1990).

[0028] FIG. 6 is a schematic diagram illustrating another embodiment of the ferromagnetic/non-

magnetic semiconductor heterojunction used in the method for generating spin-polarized conduction electrons according to the invention. A material 61 is a ferromagnetic semiconductor such as (Ga,Mn)Sb, a material 62 is a non-magnetic semiconductor such as GaSb and (Al,Ga)Sb, and a material 63 is a non-magnetic semiconductor such as InAs. The materials 61 and 62 are connected each other to constitute the junction of Type I, in which the conduction bands, the valence bands, and the energy gaps overlap partially, and the materials 62 and 63 are connected together to form the above explained junction of Type II. In such a structure, the spontaneous spin splitting is induced in the valence band of the ferromagnetic material 61 and the density of states of the valence band of the non-magnetic material 62 resonates in energy with the valence band of the ferromagnetic material 61 due to the proximity effect and spin injection effect and the spin is induced in the non-magnetic material 62 to generate spin-polarized holes. Then, the density of states of the conduction band of the non-magnetic material 63 resonates in energy with the valence band of the non-magnetic material 62 and the spin splitting is induced in the non-magnetic material 63 due to the proximity effect and the spin injection effect to generate spin-polarized electrons.
[0029] FIG. 7 is a schematic diagram showing still another embodiment of the ferromagnetic/non-magnetic semiconductor heterojunction used in the method for generating spin-polarized conduction electrons according to the invention. A material 71 is a ferromagnetic semiconductor such as (Ga,Mn)Sb, a material 72 is a non-magnetic semiconductor such as AlSb and a material 73 is a non-magnetic semiconductor such as InAs. In this structure, the material 72 serves as the energy barrier between the valence band of the material 71 and the conduction band of the material 73. Even in such a case, carriers can move between the materials 71 and 73 by the tunnel effect, although the proximity effect becomes small as compared with the case shown in FIG. 2. Therefore, the spin splitting is induced in the density of states of the conduction band of the material 73 according to the spin injection effect and spin polarized electrons are generated in the non-magnetic material 73.
[0030] According to the present invention, it is possible to generate largely spin-polarized conduction electrons due to the spin splitting of the conduction band. Moreover, the ferromagnetic/non-magnetic heterostructure according to the invention may be advantageously utilized as the spin injection electrode in the electron and/or optical device structure, because this heterostructure constitutes the semiconductor/semiconductor junction.

Claims

1. A method of generating spin-polarized conduction electrons, characterized in that the method comprises a step of providing a ferromagnetic/non-magnetic semiconductor heterojunction between a ferromagnetic semiconductor layer and a non-magnetic semiconductor layer having an energy band alignment of Type II with respect to the ferromagnetic semiconductor layer, and a step of inducing a spin splitting of a conduction band of the non-magnetic semiconductor layer by a spontaneous spin splitting of a valence band of the ferromagnetic semiconductor layer to generate spin-polarized conduction electrons.

2. A method as claimed in
claim 1, wherein said ferromagnetic/non-magnetic semiconductor heterojunction is formed by directly joining the ferromagnetic semiconductor layer and the non-magnetic semiconductor layer each other.

3. A method as claimed in
claim 2, wherein said ferromagnetic semiconductor layer is made of (Ga,Mn)Sb and said non-magnetic semiconductor layer is made of InAs.

4. A method as claimed in
claim 1, wherein said ferromagnetic/non-magnetic semiconductor heterojunction is formed by joining the ferromagnetic semiconductor layer and the non-magnetic semiconductor layer with interposing therebetween another non-magnetic semiconductor layer having an energy band alignment of Type I with respect to the ferromagnetic semiconductor layer.

5. A method as claimed in
claim 4, wherein said ferromagnetic semiconductor layer is made of (Ga,Mn)Sb, said non-magnetic semiconductor layer is made of InAs, and said another non-magnetic semiconductor layer is made of GaSb or (Al,Ga)Sb.

6. A method as claimed in
claim 1, wherein said ferromagnetic/non-magnetic semiconductor heterojunction is formed by joining the ferromagnetic semiconductor layer and the non-magnetic semiconductor layer with interposing therebetween a energy barrier layer.

7. A method as claimed in
claim 6, wherein said ferromagnetic semiconductor layer is made of (Ga,Mn)Sb, said non-magnetic semiconductor layer is made of InAs, and said energy barrier layer is made of AlSb.

8. A semiconductor device, characterized in that the device comprises a ferromagnetic semiconductor layer, and a non-magnetic semiconductor layer having an energy band alignment of Type II with respect to the ferromagnetic semiconductor, said ferromagnetic semiconductor layer and non-magnetic semiconductor layer being connected each other to form a ferromagnetic/non-magnetic semiconductor heterojunction such that a spin splitting of the conduction band of the non-magnetic semiconductor layer is induced by a spontaneous spin splitting of the valence band of the ferromagnetic semiconductor layer to generate spin-polarized conduction electrons.

9. A semiconductor device as claimed in
claim 8, wherein the semiconductor device is a circularly polarized light emitting device and a deflection of circularly polarized light is controlled by an interaction between light and spin.

10. A semiconductor device as claimed in
claim 8, wherein the semiconductor device is a spin-polarized field effect transistor, in which the ferromagnetic/non-magnetic heterostructure is used as a spin injection electrode.

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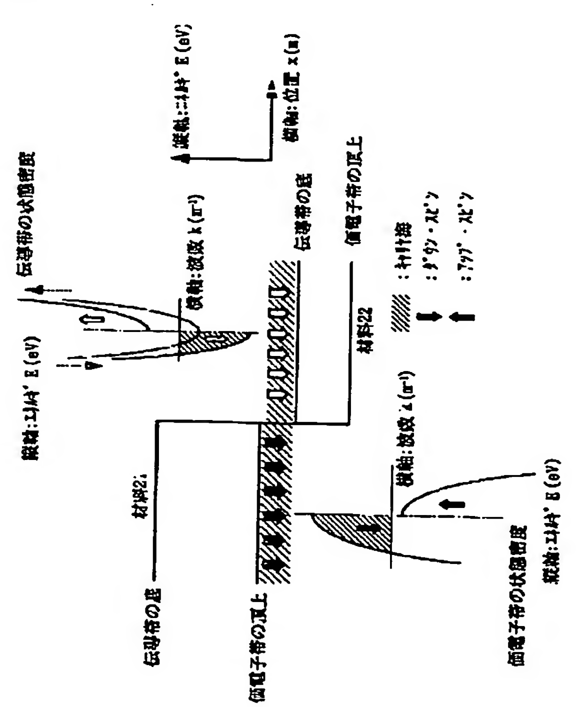
(54)【発明の名称】　スピン偏極伝導電子生成方法および半導体素子

(57)【要約】
【課題】　半導体中の電子のスピン偏極を生成する方法を提供する。
【解決手段】　強磁性半導体から成る層と、前記強磁性半導体とタイプIIのバンド配置を有する非磁性半導体から成る層とを、前記強磁性半導体層の価電子帯の自発的なスピン分裂が、前記非磁性半導体層の伝導帯のスピン分裂を誘発するように設ける。



【特許請求の範囲】

【請求項1】 強磁性半導体から成る層と、前記強磁性半導体とタイプIIのバンド配置を有する非磁性半導体から成る層とを、前記強磁性半導体層の価電子帯の自発的なスピン分裂が、前記非磁性半導体層の伝導帯のスピン分裂を誘発するように設ける工程を具えることを特徴とするスピン偏極伝導電子生成方法。

【請求項2】 強磁性半導体から成る層と、前記強磁性半導体とタイプIIのバンド配置を有する非磁性半導体から成る層とを具え、これらの層を、前記強磁性半導体層の価電子帯の自発的なスピン分裂が、前記非磁性半導体層の伝導帯のスピン分裂を誘発するように設けたことを特徴とする半導体素子。

【請求項3】 請求項2に記載の半導体素子において、該半導体素子を円偏光発光素子としたことを特徴とする半導体素子。

【請求項4】 請求項2に記載の半導体素子において、該半導体素子をスピン偏極電界効果トランジスタとしたことを特徴とする半導体素子。

【発明の詳細な説明】

【0001】

【発明の属する技術分野】本発明は、半導体素子においてスピン偏極伝導電子を生成する方法に関する。本発明は、さらに、スピン偏極伝導電子を含む半導体素子に関する。

【0002】

【従来の技術】半導体内のスピン偏極伝導電子の生成は、半導体電子材料にスピン自由度を新たに加えるものであり、将来のデバイス応用に向けての研究が広く進められている。このようなスピン偏極伝導電子を含む半導体素子は、スピン電界効果トランジスタ、スピン偏極走査型トンネル顕微鏡、スピンメモリ素子、円偏光素子等への応用が期待されている。

【0003】従来のスピン偏極した電子を生成する技術としては、金属磁性体電極を用いてスピン偏極電子を半導体中に注入する方法がある。しかしながらこの方法では、金属/半導体界面により生じるショットキ障壁のため、半導体中のスピン偏極は僅かに変化するのみであった。

【0004】また、半導体を構成する原子の一部を磁性原子に置き換え、半導体自身を磁性半導体にして電子に偏極を生じさせることも可能であるが、磁性スピンと電子の相互作用が小さいため、スピン偏極は僅かにしか生じない。一方このような磁性半導体の正孔と磁性スピンの相互作用は大きく、正孔に大きなスピン偏極を与えることは可能であるが、スピン－軌道相互作用のためスピン緩和時間が極めて高速であり、エレクトロニクス分野への応用が困難であった。

【0005】

【発明が解決しようとする課題】したがって本発明の目的は、半導体中の電子（伝導帯中のキャリヤ）のスピン偏極を生成するのに有効な方法を提供することである。また、本発明の他の目的は、この方法において生成したスピン偏極伝導電子を含む半導体素子を提供することである。

【0006】

【課題を解決するための手段】本発明によるスピン偏極伝導電子生成方法は、強磁性半導体から成る層と、前記強磁性半導体とタイプIIのバンド配置を有する非磁性半導体から成る層とを、前記強磁性半導体層の価電子帯の自発的なスピン分裂が、前記非磁性半導体層の伝導帯のスピン分裂を誘発するように設ける工程を具えることを特徴とする。半導体同士の接合において、一方の価電子帯がエネルギバンド図で他方の伝導帯の上に位置する配置をタイプIIのバンド配置と呼ぶ。強磁性体半導体層と、この強磁性体半導体層とタイプIIのバンド配置を有する非磁性半導体層とを接合すれば、強磁性半導体の価電子帯の自発的なスピン分裂が、隣接する非磁性半導体の伝導帯のスピン分裂を誘発し、非磁性半導体中の電子のスピン偏極が生成される。

【0007】本発明による半導体素子は、強磁性半導体から成る層と、前記強磁性半導体とタイプIIのバンド配置を有する非磁性半導体から成る層とを具え、これらの層を、前記強磁性半導体層の価電子帯の自発的なスピン分裂が、前記非磁性半導体層の伝導帯のスピン分裂を誘発するように設けたことを特徴とする。

【0008】

【発明の実施の形態】本発明によるスピン偏極伝導電子生成方法は、磁性半導体の価電子帯が自発的にスピン分裂を誘発することを利用し、それに隣接する非磁性体の伝導帯のスピン分裂を誘発し、半導体中の電子のスピン偏極を生成する。半導体同士の接合において、一方の半導体の伝導帯と他方の半導体の価電子帯が重なるものをタイプIIの接合と呼ぶ。以下、本発明による方法における非磁性体と強磁性体のタイプIIの接合を、通常の非磁性半導体同士のタイプIIの接合と比較して説明する。

【0009】図1は、通常の半導体ヘテロ接合を説明する図である。この接合において、材料１１を、例えば、ＧａＳｂ等の非磁性半導体とし、材料１２を、材料１１とタイプIIのバンド配列をとる非磁性半導体の、例えば、ＩｎＡｓ等とする。この図の左下に示すグラフは、材料１の価電子帯の状態密度を表し、縦軸をエネルギＥ（ｅＶ）とし、横軸を波数ｋ（m^{-1}）とする。右上に示すグラフは、材料２の伝導帯の状態密度を表し、縦軸をエネルギＥ（ｅＶ）とし、横軸を波数ｋ（m^{-1}）とする。中央に示すグラフは、この接合におけるエネルギバンドの様子を表し、縦軸をエネルギＥ（ｅＶ）とし、横軸を位置ｘ（ｍ）とする。このような接合において、材料１１の価電子帯の状態密度はスピン分裂せず、したがって、材料１２の伝導帯にスピン偏極は生じない。

【0010】図2は、本発明によるスピン偏極伝導電子生成方法を実現する接合を説明する線図である。この接合において、材料21を、例えば、(Ga,Mn)Sb等の強磁性半導体とし、材料22を、材料21とタイプIIのバンド配列をとる非磁性半導体の、例えば、InAs等とする。図1と同様に、この図の左下に示すグラフは、材料21の価電子帯の状態密度を表し、縦軸をエネルギE(eV)とし、横軸を波数k(m^{-1})とする。右上に示すグラフは、材料22の伝導帯の状態密度を表し、縦軸をエネルギE(eV)とし、横軸を波数k(m^{-1})とする。中央に示すグラフは、この接合におけるエネルギバンドの様子を表し、縦軸をエネルギE(eV)とし、横軸を位置x(m)とする。このような接合において、材料21は、磁性スピンと正孔の交換相互作用により自発的に価電子帯がスピン分裂する。材料22の伝導帯の状態密度は、材料21の価電子帯とエネルギ的に共鳴し、近接効果およびスピン注入効果によりスピン分裂が生じ、スピン偏極した電子が生成される。

【0011】図3は、本発明による磁性半導体/半導体スピン素子30の構造を示す線図である。半導体基板32上に薄膜作成方法で成長した電子素子、光素子構造34の上に、非磁性半導体層36を介して強磁性半導体層38を成長させる。非磁性半導体層36を、例えば、InAs等とする。強磁性半導体層38を、例えば、(Ga,Mn)Sb層等とするが、Mn以外にも磁性元素としてその他の遷移金属元素、希土類元素を用いることもできる。これらの半導体素子結晶を、分子線エピタキシ法などの薄膜結晶作成法で作成する。(Ga,Mn)Sb層の成長は、550℃前後の高温でも成長可能であるが、III−V族半導体中の磁性元素の固溶度が低いため、極端に非平衡な低温(例えば、250℃前後)での成長が有利である。このような構造にすれば、図2の参照と共に説明したように非磁性半導体層36の電子にスピン偏極が生じるため、電子素子、光素子に電子スピンという新たな自由度を導入することができるようになる。また、この図の実施形態においては、電子素子、光素子構造34と、非磁性半導体層36とは、別個の半導体であるが、例えば、スピン偏極電界トランジスタ等に用いた場合には非磁性半導体層36自身が素子材料になり、この場合、電子素子、光素子構造34は必要なくなる。

【0012】図4は、本発明の一実施形態である円偏光発光素子40の構造を示す斜視図である。この円偏光発光素子40は、図3の半導体スピン素子と同様の半導体基板42、非磁性半導体層46および強磁性半導体層48を具え、さらに発光素子構造44を具える。この場合、光とスピンの相互作用により、光の偏向を制御することができるようになる。

【0013】また、この構造を電極とするスピン偏極電子注入電極として応用できる。図5は、本発明の他の実施形態であるスピン偏極電界効果トランジスタの構造を示す断面図である。このスピン偏極電界効果トランジスタ50は、一般的な電界効果トランジスタ構造を有するが、上述したような接合された非磁性半導体層51および強磁性半導体層52をスピン偏極電子注入電極として有する。スピン偏極電界効果トランジスタについては、S.Datta and B.Das,App.Phys.Lett.56,665(1990)を参照されたい。

【0014】図6は、本発明によるスピン偏極伝導電子生成方法を実現する他の接合を説明する図1および図2と同様の図である。材料61を、例えば、(Ga,Mn)Sb等の強磁性半導体とし、材料62を、例えば、GaSb、(Al,Ga)Sb等の非磁性半導体とし、材料63を、例えば、InAs等の非磁性半導体とする。ここで、材料61および62は、伝導帯同士、価電子帯同士、エネルギギャップが部分的に重なるタイプIの接合であり、材料62および63は、タイプIIの接合である。このような場合、強磁性体の材料61の価電子帯は自発的にスピン分裂し、材料62の価電子帯の状態密度は、材料61の価電子帯とエネルギ的に共鳴し、近接効果およびスピン注入効果によりスピン分裂が生じ、スピン偏極した正孔が生成される。さらに、材料63の伝導帯の状態密度は、材料62の価電子帯とエネルギ的に共鳴し、近接効果およびスピン注入効果によりスピン分裂が生じ、スピン偏極した電子が生成される。

【0015】図7は、本発明によるスピン偏極伝導電子生成方法を実現するさらに他の接合を説明する図1、図2および図6と同様の図である。材料71を、例えば、(Ga,Mn)Sb等の強磁性半導体とし、材料72を、例えば、AlSb等とし、材料73を、例えば、InAs等の非磁性半導体とする。この場合、材料72が、材料71の価電子帯と材料73の伝導帯の間のエネルギ障壁となっている。このような場合でも、トンネル効果により材料71および73間でキャリヤの往来が生じるため、図2に示す場合に比べて近接効果は小さくなるが、スピン注入効果によって材料73の伝導帯の状態密度にスピン分裂が生じ、スピン偏極した電子が生成される。

【0016】

【発明の効果】本発明によれば、伝導帯がスピン分極しているため大きくスピン偏極した伝導電子が生成される。またこのような構造でスピン注入電極を作製した場合においても半導体/半導体の接合であるため、スピン注入電極として利用できる。

【図面の簡単な説明】

【図1】 従来の半導体へテロ結合を説明する図である。

【図2】 本発明によるスピン偏極伝導電子生成方法を実現する接合を説明する図である。

【図3】 本発明による磁性半導体/半導体スピン素子

の構造を示す線図である。

【図4】 本発明による円偏光発光素子の斜視図である。

【図5】 本発明によるスピン偏極電界効果トランジスタの断面図である。

【図6】 本発明によるスピン偏極伝導電子生成方法を実現する他の接合を説明する図である。

【図7】 本発明によるスピン偏極伝導電子生成方法を実現するさらに他の接合を説明する図である。

【符号の説明】

21、61、71 強磁性半導体材料

11、12、22、62、63、72、73 非磁性体半導体材料

30 磁性半導体／半導体スピン素子

32、42 半導体基板

34 電子素子、光素子構造

36、46、56 非磁性半導体層

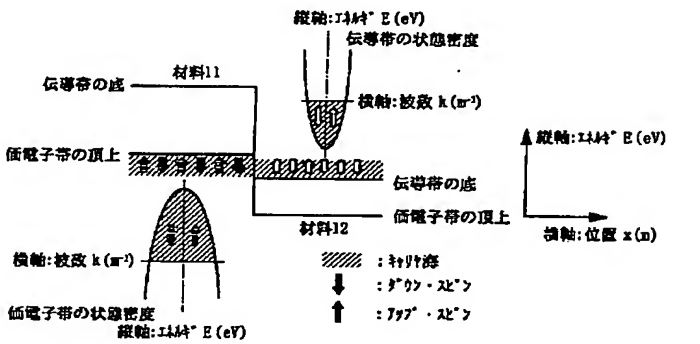
38、48、58 強磁性半導体層

40 円偏光発光素子

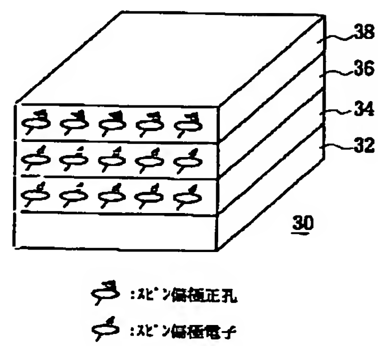
44 発光素子構造

50 スピン偏極電界効果トランジスタ

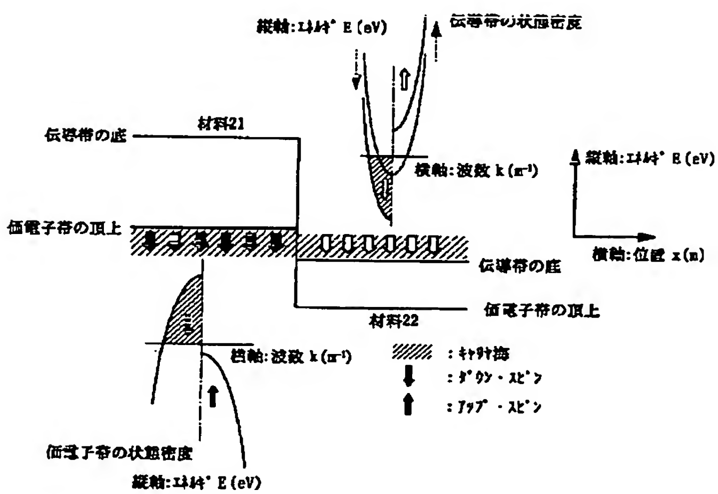
【図1】



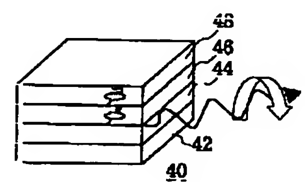
【図3】



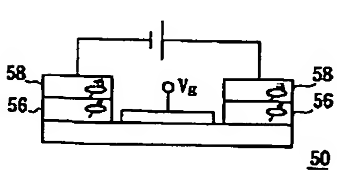
【図2】



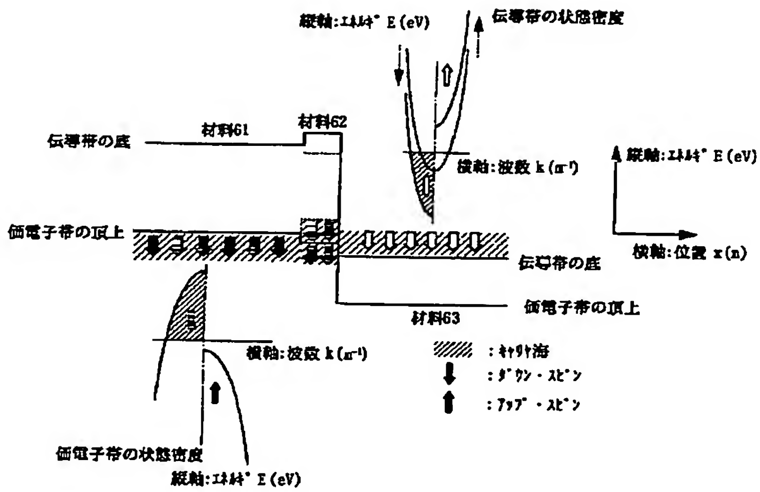
【図4】



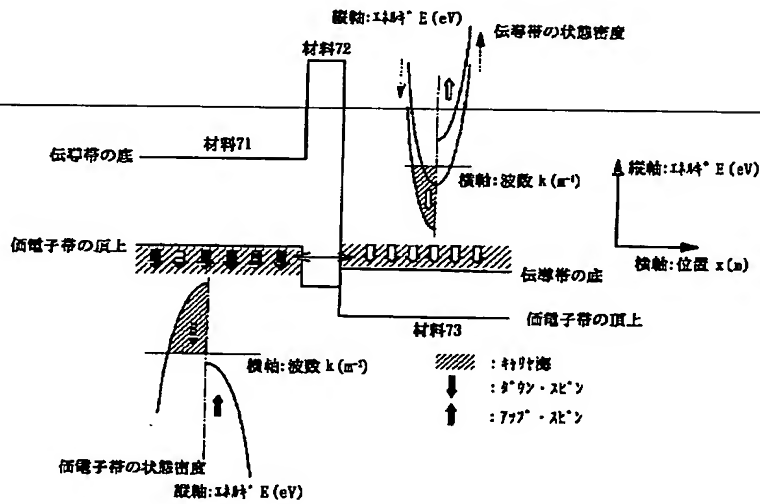
【図5】



【図6】


縦軸:ｴﾈﾙｷﾞ E (eV)
伝導帯の状態密度
材料62
伝導帯の底
材料61
横軸:波数 k (m⁻¹)
縦軸:ｴﾈﾙｷﾞ E (eV)
価電子帯の頂上
横軸:位置 x (m)
伝導帯の底
価電子帯の頂上
材料63
横軸:波数 k (m⁻¹)
：ｷｬﾘｱ海
：ﾀﾞｳﾝ・ｽﾋﾟﾝ
：ｱｯﾌﾟ・ｽﾋﾟﾝ
価電子帯の状態密度
縦軸:ｴﾈﾙｷﾞ E (eV)

【図7】


縦軸:ｴﾈﾙｷﾞ E (eV)
伝導帯の状態密度
材料72
材料71
伝導帯の底
横軸:波数 k (m⁻¹)
縦軸:ｴﾈﾙｷﾞ E (eV)
価電子帯の頂上
横軸:位置 x (m)
伝導帯の底
価電子帯の頂上
材料73
横軸:波数 k (m⁻¹)
：ｷｬﾘｱ海
：ﾀﾞｳﾝ・ｽﾋﾟﾝ
：ｱｯﾌﾟ・ｽﾋﾟﾝ
価電子帯の状態密度
縦軸:ｴﾈﾙｷﾞ E (eV)